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16 Abstract


An experiment was conducted at West Lafayette, Indiana in 1979 to quantitatively describe the interaction of the solar illumination angle and row azimuth angle on the measured reflectance factor (RF) of soybean canopies consisting of 11 plots. Nine of the plots were planted in 71 cm wide rows; the other plots were of bare soil and soybeans with 100 percent soil cover. Reflectance factor data in four spectral bands, 0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1 μm, were taken at 15 minute intervals during three clear days, August 12 and 31 and September 19 over nine plots of differing azimuthal direction with a Landsat-band radiometer (Exotech Model 100) at 5.2 meters above the soil.

Diurnal changes of nearly 140 percent were observed in the red wavelength region when canopies covered 64 percent of the soil. The amount of shadow observed was a function of the plant geometry and row width. As soil cover approached 100 percent, the diurnal changes diminished. A function that describes the solar illumination angle with respect to the row azimuth explained most of the diurnal variation in the measured RF. Variation in near infrared response was much less and did not appear to be as strongly related to sun-row angle interactions. The ratio, near infrared/red, was highly sensitive to sun angle-row direction interactions, whereas the greenness function, utilizing all four spectral bands, was not.


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## Introduction

Understanding the effect of the interactions between solar illumination and crop canopy geometry on the spectral response is necessary to utilize reflectance factor data effectively. Numerous models have been proposed to explain and predict the measured reflectance factor of plant canopies as a function of plant geometry, sun angle, and view angle (Suits, 1972; Smith et al., 1975; Richardson et al., 1975). The models by Suits and Smith deal with a canopy with no horizontal spatial variations.

Richardson et al. (1975) modeled the reflectance of a row crop, with distinct horizontal spatial variations, as a function of plant, soil, and shadow components. By illuminating a surface covered with various shaped objects, Egbert (1977) was able to explain 80 to 85 percent of the variance in the reflectance measurements due to shadows. A model suggested by Jackson et al. (1979) assumes an incomplete canopy of rectangular-shaped rows. The fractions of sunlit and shaded soil and vegetation viewed are calculated as a function of view angle for a particular canopy condition, described by plant cover, height/width ratio, row spacing and direction, time of day, day of year, latitude, and size of the radiometer resolution element.

Studies of the effect of sun zenith angle on reflectance generally have supported the predictions of the Suit's canopy reflectance model that the reflectance factor should increase as the solar elevation

increases (Colwell, 1974; Chance and LeMaster, 1977). Colwell (1974) attributes this to changes in the amount of shadow within the canopy. Field data have shown minor to significant increases in the infrared response with decreasing sun elevations (Duggin, 1977; Chance and LeMaster, 1977; Jackson et al., 1979). Crecelius (1978) noted symmetric and non-symmetric components about solar noon that influenced the observed variation in reflectance throughout the day. The symmetric component, solar angle, explained the majority of the observed variation. Other effects, such as drying of the soil surface and plant wilting will be asymmetric about solar noon and may be significant factors to consider.

Further investigation of reflectance factor data taken in 1978 over incomplete soybean canopies revealed possible time of day effects in the Landsat band regions as illustrated in the red, 0.6-0.7 μm, and the near infrared, 0.8-1.1 μm, in Figure 1. Plots were planted in a north-south row direction. Both bands were plotted with and without a 1.5 hour time restriction about solar noon. Low responses were noted over those plots that were measured more than 1.5 hours from solar noon. These changes in RF resulted from shadows between the rows and a lower response from the soil component.

The objective of this research was to model the reflectance of a soybean canopy as a function of row width, row direction, and solar azimuth and zenith angles. The hypothesis was that by varying only the

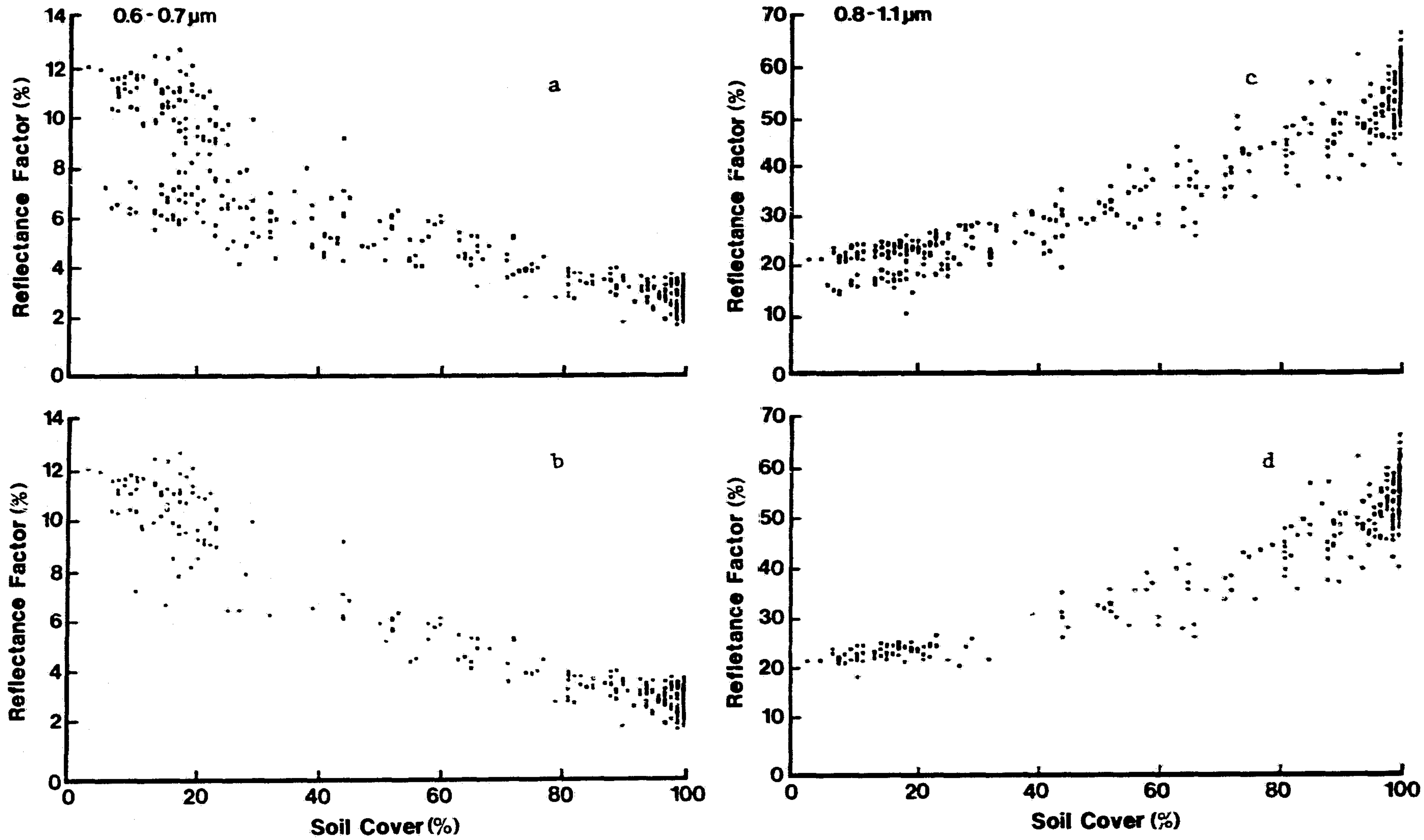



Figure 1. Time of day effect on the RF seen in the 1978 data for the red (0.6-0.7 µm) and the near infrared (0.8-1.1 µm) wavelength regions. (a,c) All 1978 data minus dates which include wet soil and/or senescing vegetation. (b,d) Same as a and c above, but only includes data in the three hour time period centered about solar noon.

row direction, the variation in reflectance would be explained entirely by changes in sun zenith and azimuth angle with respect to row direction.

## Materials and Methods

### Experimental Conditions

The experiment was conducted in 1979 on the Purdue Agronomy Farm. Soybeans (Glycine max (L.) Merr. "Amsoy 71") were planted on a Chalmers silty clay loam (typic Argiaquoll) on June 25, 1979. Soybeans were used because they have dense foliage with distinct row patterns through much of the season. This is in contrast to many of the other major crops such as wheat and corn that have a much more complex canopy geometry and shadow pattern. Because of extended periods of cloudy days early in the season, spectral data were collected only on development stages after full bloom.

The experiment consisted of 11 randomly arranged plots which were 3.5 m wide and 5.2 m long (Figure 2). Nine plots were planted in 71-cm rows with the following azimuthal directions: 0-180, 30-210, 60-240, 90-270, 105-285, 120-300, 135-315, 150-330, and 165-345 degrees from north. Another plot was planted in 25-cm wide east-west and north-south rows to obtain a canopy with negligible row effects. A bare soil plot was included to monitor the sunlit soil background reflectance of the soybean plots. Row directions were selected to favor data collection during the morning hours when cloud-free conditions were more likely.

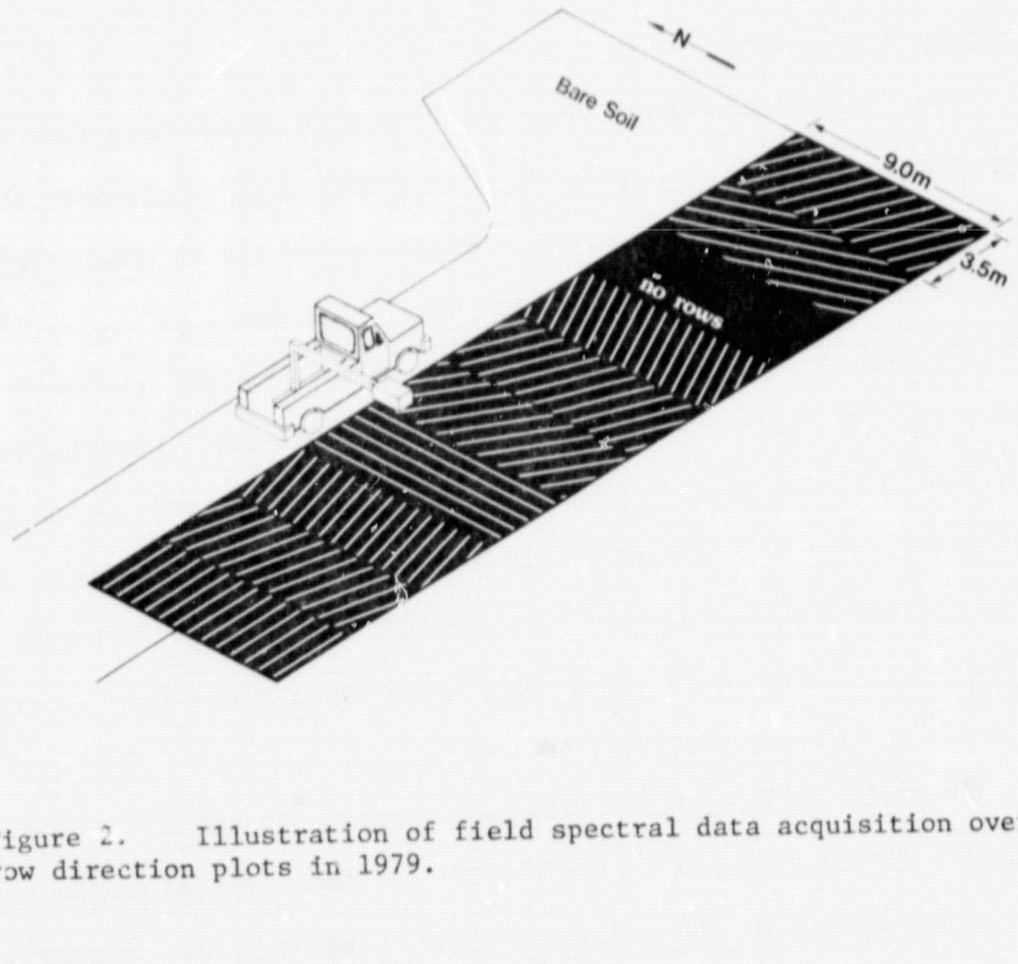



Figure 2. Illustration of field spectral data acquisition over the row direction plots in 1979.

Three development stages with 65, 78, and 94 percent soil cover on the 71-cm rows were represented with the three measurement dates. The canopy with 78 percent soil cover was obtained by trimming a near full canopy just prior to the start of senescence. The cross sectional shape of the canopy was determined by placing a large piece of poster board in the canopy, perpendicular to the row azimuth, at several locations and drawing the perimeter of the canopy on the board. The canopy shapes for each date are illustrated in Figure 3.

Spectral Measurements

Radiance measurements, used to determine reflectance factor (RF), were taken over all the plots with a Landsat band radiometer (Exotech Model 100) at 15-minute intervals throughout the day on three clear days (August 12, August 31, and September 19). Nicodemus et al. (1977) and Robinson and Biehl (1979) descibe the conditions and proceedures for obtaining the reflectance factor, which closely approximates the bidirectional reflectance factor. The Exotech 100 is a 4-band radiometer with a 15-degree field of view that acquires data in the following wavelength regions: 0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1 μm. Data were taken only under near cloud-free conditions (especially in the vicinity of the sun).

A mobile truck-mounted radiometer system was used for quick and efficient data collection in the field. A boom mounted on the back of the truck permitted the radiometer and a motor-driven camera to be placed 5.2 m above the crop canopy and 3.5 m from the truck. Spectral data were collected over two locations in each plot on August 12 and

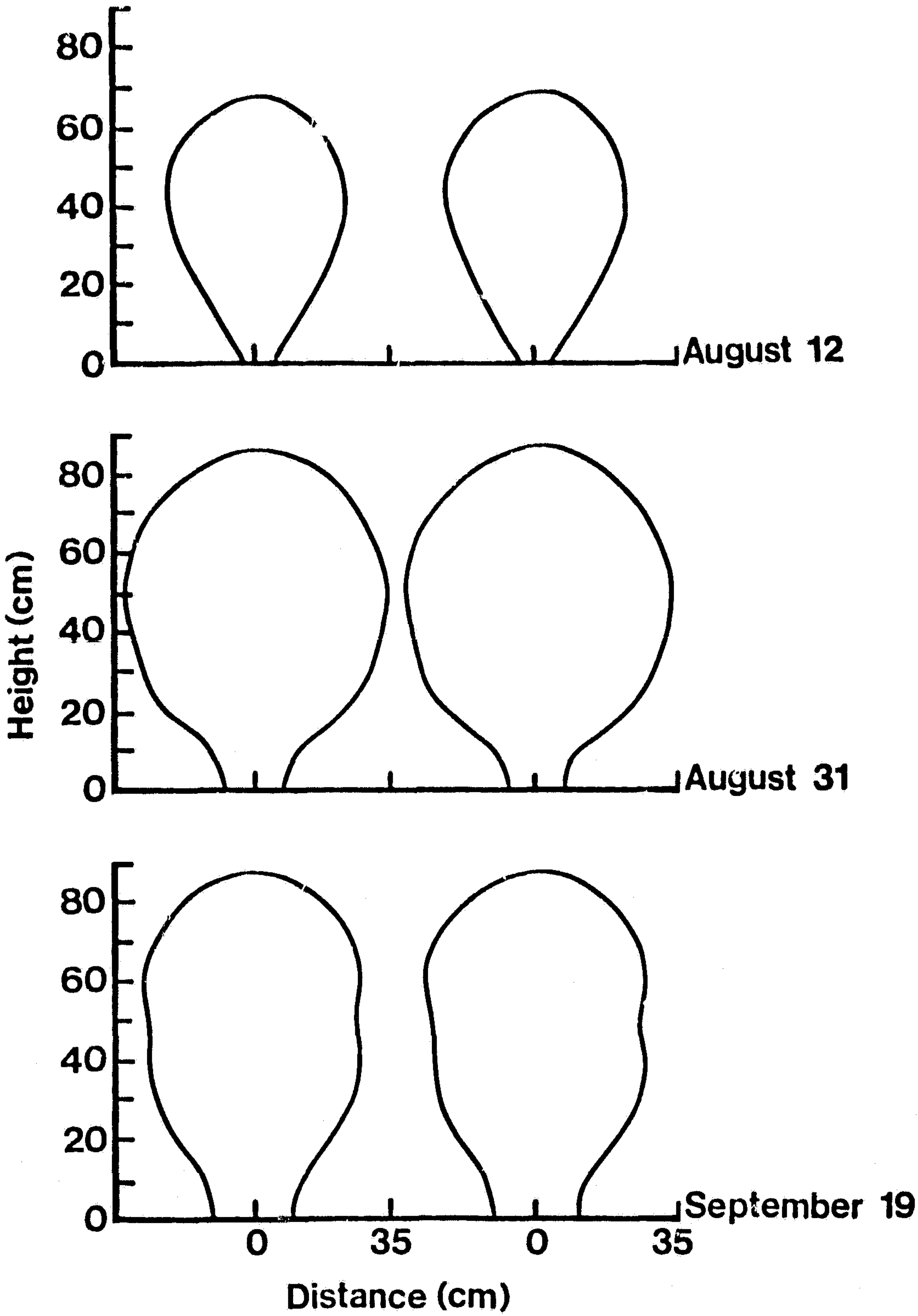



Figure 3. Soybean canopy shapes and dimensions for three dates of data collection.

over four locations in each plot on August 31 and September 19. The instruments were carefully leveled to obtain all spectral data at a nadir look angle. Several measurements were taken over each plot and averaged to insure a representative sampling of the plot and to avoid biased values for on-row or off-row measurements. Measurements in all bands were taken concurrently and recorded by a printing data logger. During data collection, photographs were taken periodically over each plot for soil cover determination and shadow assessment.

## Agronomic Measurements

Agronomic measurements included plant height, leaf area index, maturity stage (Fehr and Caviness, 1977), surface soil moisture, total fresh and dry biomass, and stem, pod, and green leaf dry biomass. Percent soil cover was determined by placing a grid over the vertical photograph and counting the intersections occupied by green vegetation.

## Data Analysis

The reflectance factor data were analyzed as band means. The reflectance data were transformed into greenness as described by Kauth and Thomas (1976) for Landsat MSS data and modified for spectrometer data (Malila and Gleason, 1977). The data transformation was: Greenness $= \left[(\text{Band3} * 0.17289) + (\text{Band4} * 0.59538)\right] - \left[(\text{Band1} * 0.48935) + (\text{Band2} * 0.61249)\right]$. Band1 to band4 refer to the RF measured in the four Landsat bands. The near infrared/red reflectance ratio $\left[(0.8\text{-}1.1\ \text{um})/(0.6\text{-}0.7\ \mu\text{m})\right]$ was also considered in the analysis. Analysis of variance and Newman-Keuls tests were performed to determine significant effects of row-solar angle interaction and RF.

## Results and Discussion

The maximum response of RF to changes in sun angle occurred when the sun azimuth angle was equal to the row azimuth angle (Figure 4a). Diurnal changes in RF of nearly 140 percent were observed in the red wavelength region, 0.6-0.7 μm, on August 12. The highest reflectance values were obtained when the soil was sunlit and the lowest, when the soil was shaded. Diurnal variations in the RF in the near infrared wavelength region, 0.8-1.1 μm, were lower (relative to the minimum RF value observed) than that noted in the visible region and not as clearly related to sun-row interactions (Figure 4b). Note the absolute changes in RF are about the same. The shadows of the near infrared region may not be as dark as those observed in the visible region due to low pigment absorption and multiple scattering in the canopy (Colwell, 1974).

The effect of sun-row azimuth interactions are shown in Figure 5. The reflectance was plotted over time for three plots of different row directions. The peak response in the red wavelength region for the three plots was not only at different times, but also in order of the row azimuth. Again the peak response was when the sun was shining down the rows, lighting the soil surface, and thus giving a higher reflectance reading.

The diurnal response in the red wavelength region for two of the key canopy components, sunlit soil and vegetation, are shown in Figure 6. Very little change in reflectance factor was observed as a function of zenith angle for either the plot containing bare soil or the plot

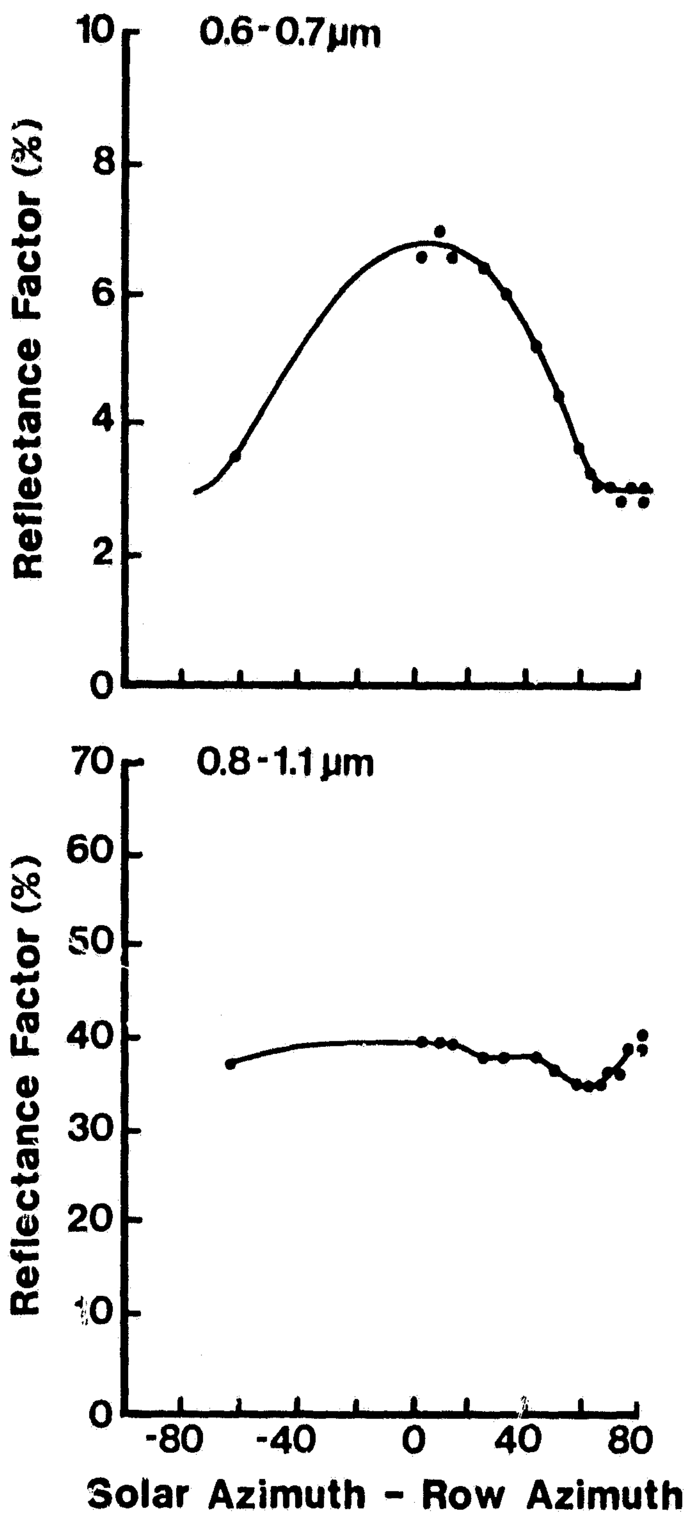



Figure 4. Changes in the BRF in (a) the red wavelength band (0.6-0.7 µm) and (b) the near infrared wavelength band (0.8-1.1 µm) plotted against the difference between solar and row azimuth. Row azimuth=180°.

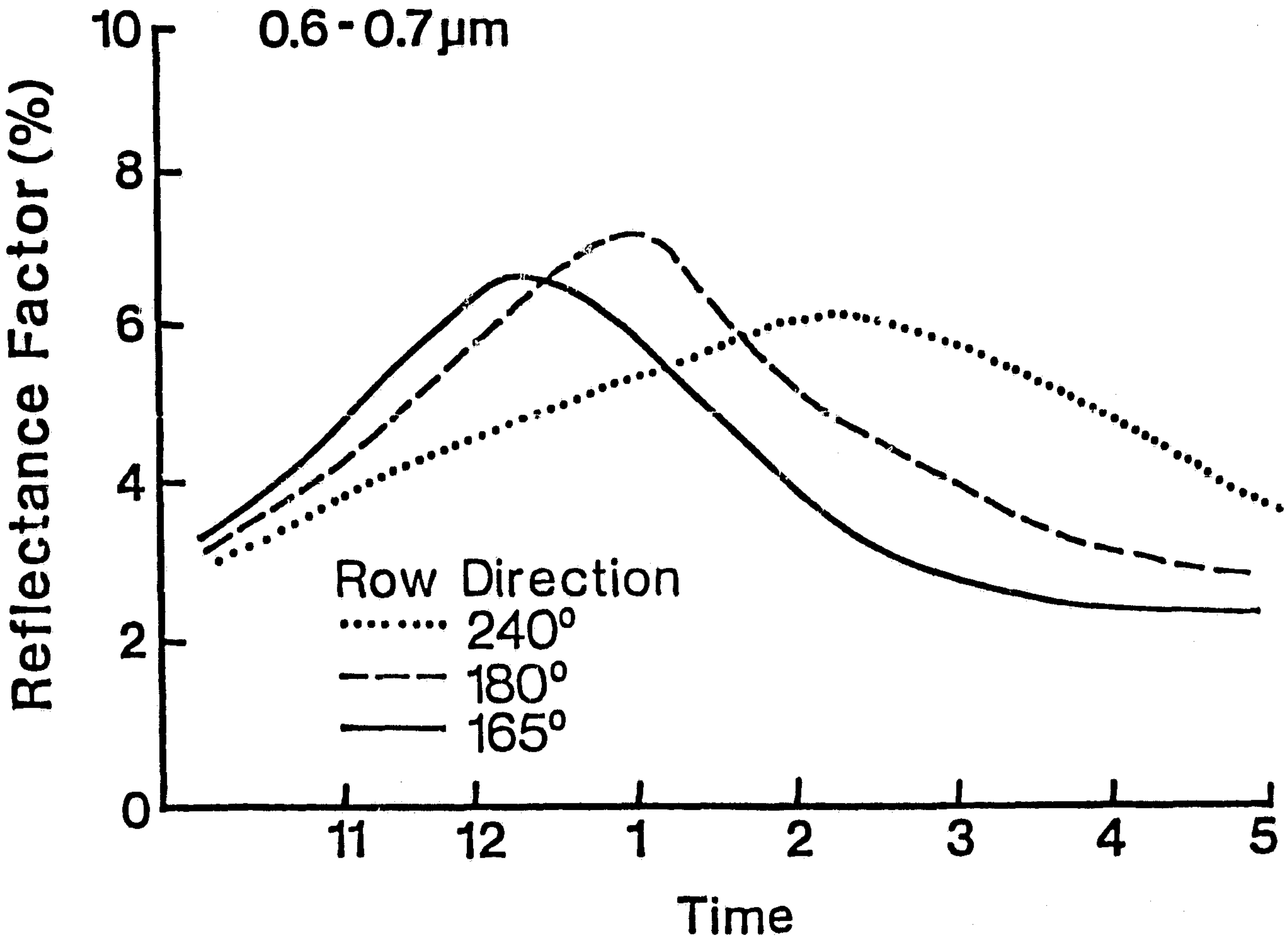



Figure 5. RF in the red wavelength region (0.6-0.7 µm) for three row directions over time on August 12, 1979.

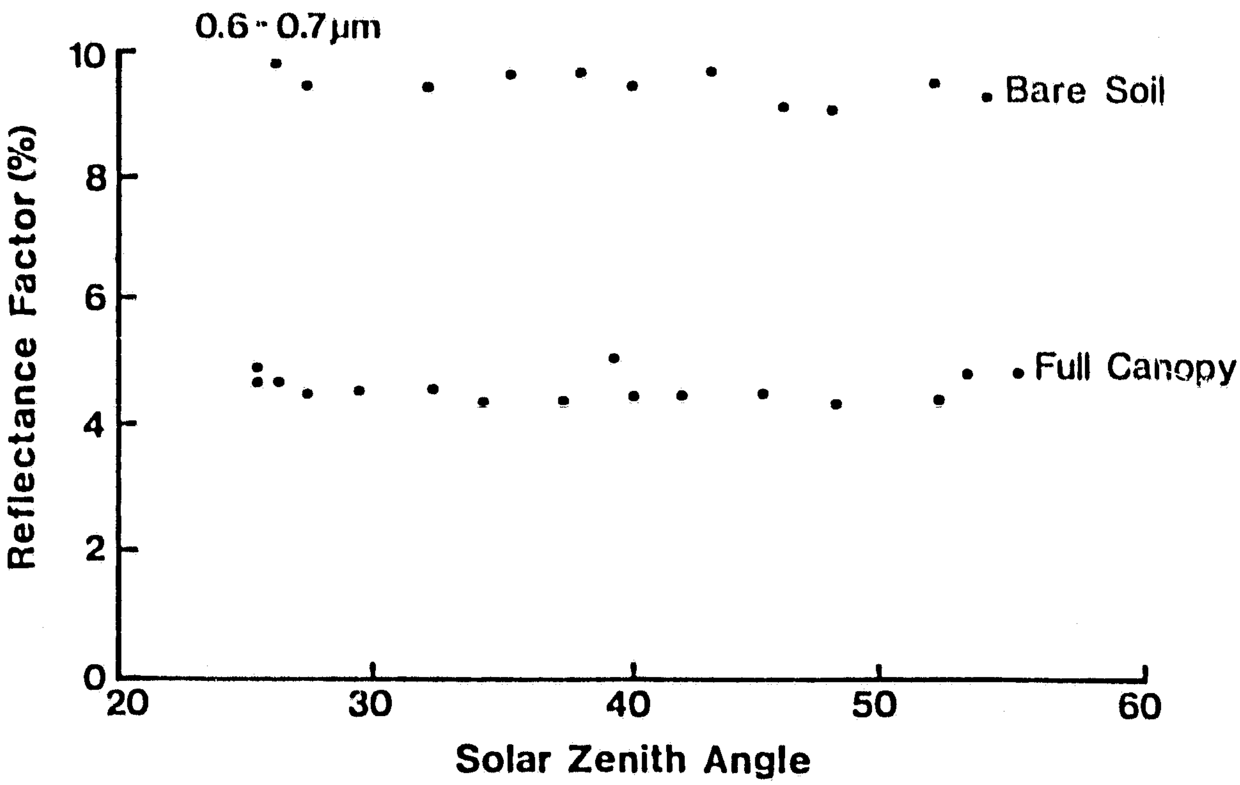
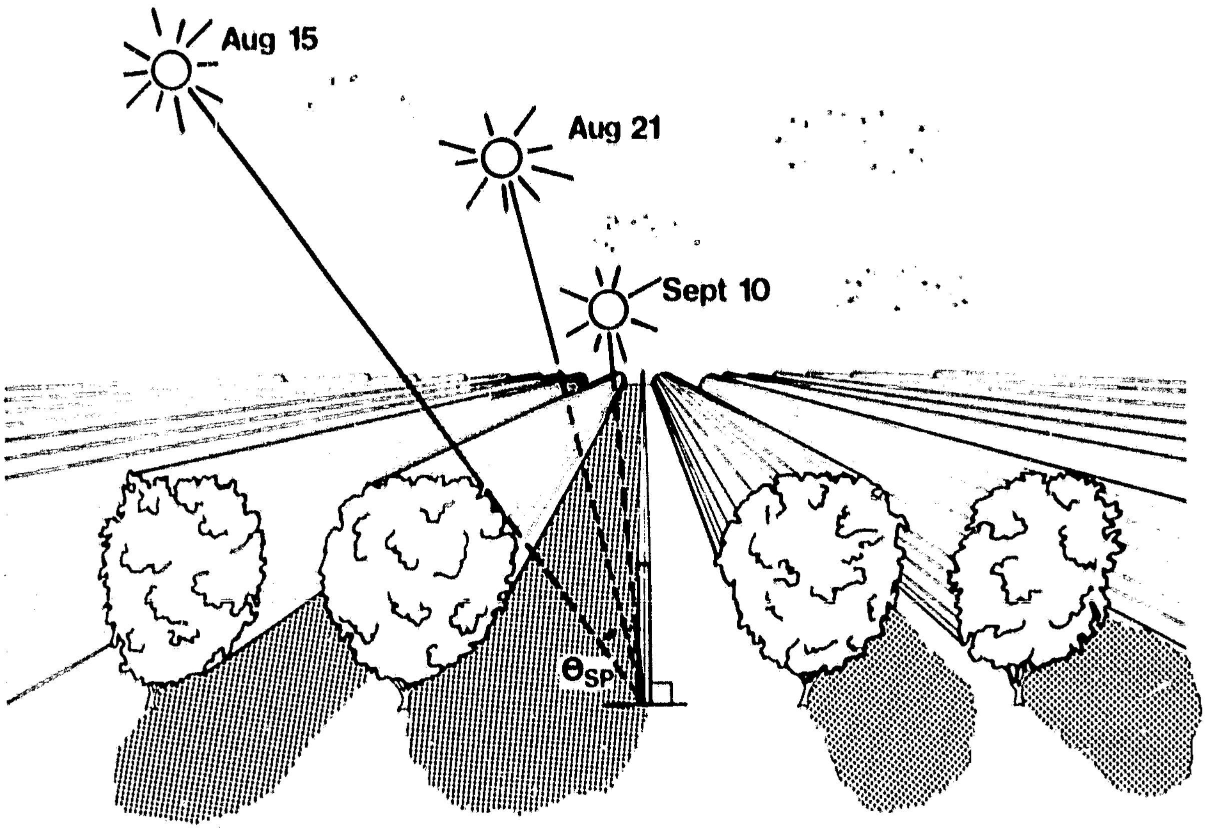



Figure 6. Reflectance factor in the red wavelength (0.6-0.7 μm) for the bare soil and full vegetative canopy plots against changes in zenith angle on August 12, 1979.

with 100 percent soil cover. Note the large differences between the sunlit soil and sunlit vegetation. Interaction of the canopy shape and size, and soil width with the sun angle produces varying amounts of shadow cast on both the soil and the vegetation. Thus, it may be that the diurnal variations in RF observed in Figures 4 and 5 were caused by changes in the amount of shadow in the field of view of the instrument.

Equations to predict the shadow cast by rectangular or spherical rows as the sun zenith and azimuth change throughout the day have been defined by many investigators (Idso and Baker, 1972; Jackson et al., 1979; Verhoff and Bunnik, 1978). For this study, an equation was used to express the solar zenith ($\theta$) and azimuth angle ($\phi$) in relation to a projected ray onto a plane perpendicular to the row azimuth. This function, called the projected solar angle, $\theta sp = \tan^{-1}(\tan\theta \sin\phi)$, is illustrated in Figure 7.

The response of the red, near infrared, near infrared/red reflectance ratio, and greenness transformation to changes in $\theta sp$ on August 12 are presented in Figure 8. The near infrared/red ratio and the greenness transformation are often related to changes in plant biomass, soil cover, and/or leaf area index. If the diurnal changes are expressed as a percent increase in response relative to the minimum value observed that day, the red and near infrared/red ratio were quite sensitive to changes in $\theta sp$, whereas the greenness and the near infrared region were not. The near infrared wavelength region does show similar absolute changes in response during the day, but the pattern is not as clearly related to the changes in sun-row angle and the variation about the mean for any given $\theta sp$ is much higher for the near infrared region.




| Date | Time | Solar Angle Zenith | Solar Angle Azimuth | $\Theta_{sp}$ |
|---|---|---|---|---|
| Aug 15 | 12:00 | 26.3 | 180.0 | 26.3 |
| Aug 21 | 2:09 | 40.1 | 234.2 | 26.3 |
| Sept 10 | 4:49 | 73.7 | 261.7 | 26.3 |

Figure 7. Illustration of the solar projected angle $\theta_{sp}$ as observed when looking to the west. Three dates and the corresponding observation times result in the same shadow pattern and $\theta_{sp} \approx 26°$.

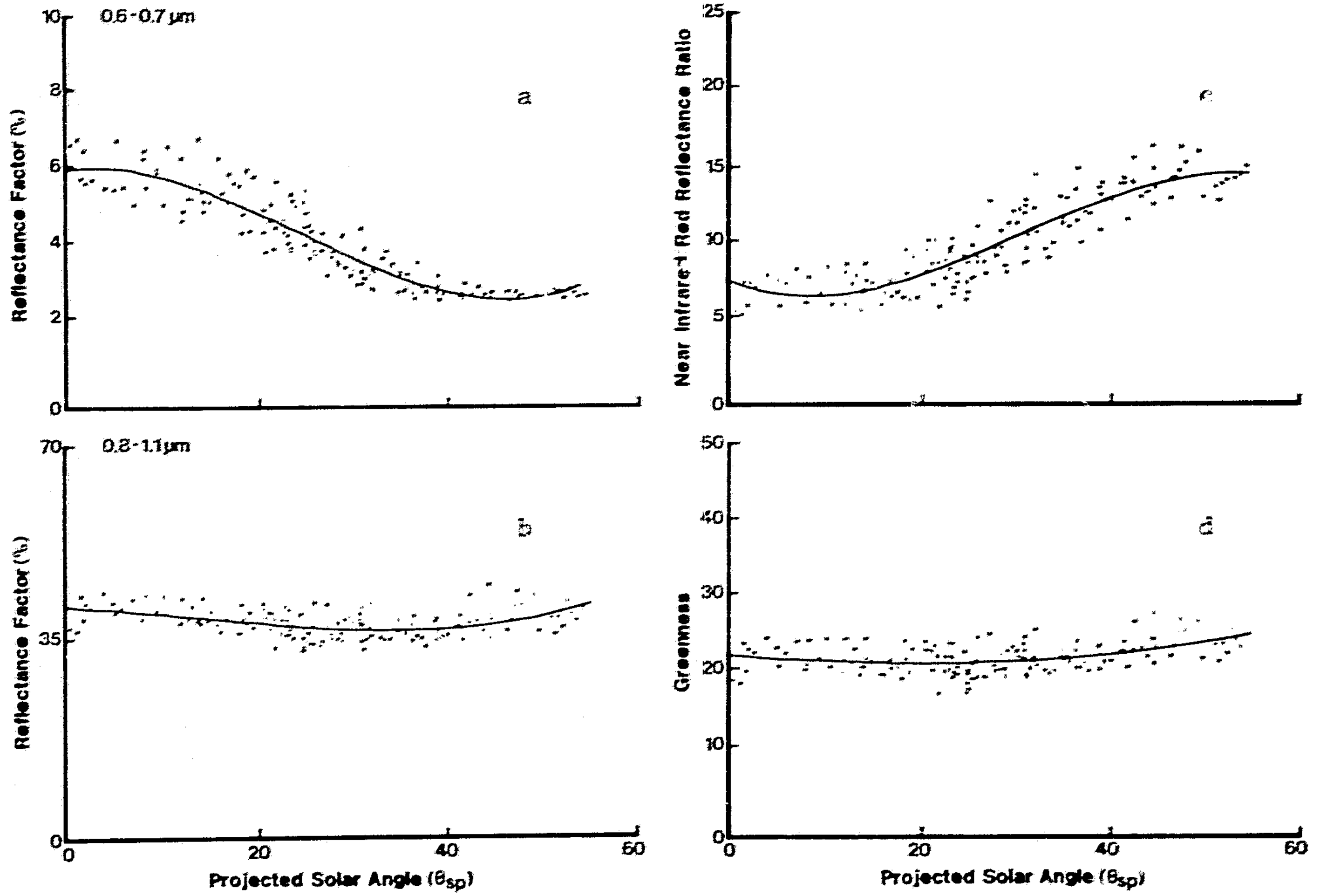



Figure 8. Relationship of four spectral variables to changes in $\theta sp$. (a) RF (0.6–0.7 µm) (b) RF (0.8–1.1 µm) (c) near infrared/red reflectance ratio (d) greenness. Data collected August 12, 1979.

The response in the red (0.6-0.7 μm) wavelength band has been plotted as a function of θsp for the three diurnal studies in 1979 (Figure 9). The canopies with lower soil covers, 64 and 78 percent, showed greater changes in reflectance due to changing sun angle than the near full canopy of 94 percent soil cover. The RF of the canopies with 94 percent soil cover changed only slightly more during the day than the RF of the full canopy. The first two dates appeared to have two functions present, the first being highly dependent on ϕsp, the second independent of θsp.

The dependent zone, where the RF is changing rapidly with changes in θsp, is a function of the sunlit soil reflectance and the vegetation reflectance (Figure 9). The variation about the mean might be due to local variations in soil cover or, possibly, instrument position about the row at low sensor altitudes. Some of this variation was thought to be due to the interaction of sun zenith angle with the surface roughness of the canopy, with large zenith angles causing longer shadows and thus lower reflectance. However, no evidence of this was apparent from the analysis of the data.

In the independent region (Figure 9), where the soil surface was completely shadowed, the measured reflectance was a function of by one variable, the percent soil cover. Just as for the dependent zone, local variations in soil cover might cause the observed amount of variation about the mean. The critical angle, beyond which a change in the projected angle no longer results in a change in RF, shifts to lower θsp's for higher soil covers or canopy heights.

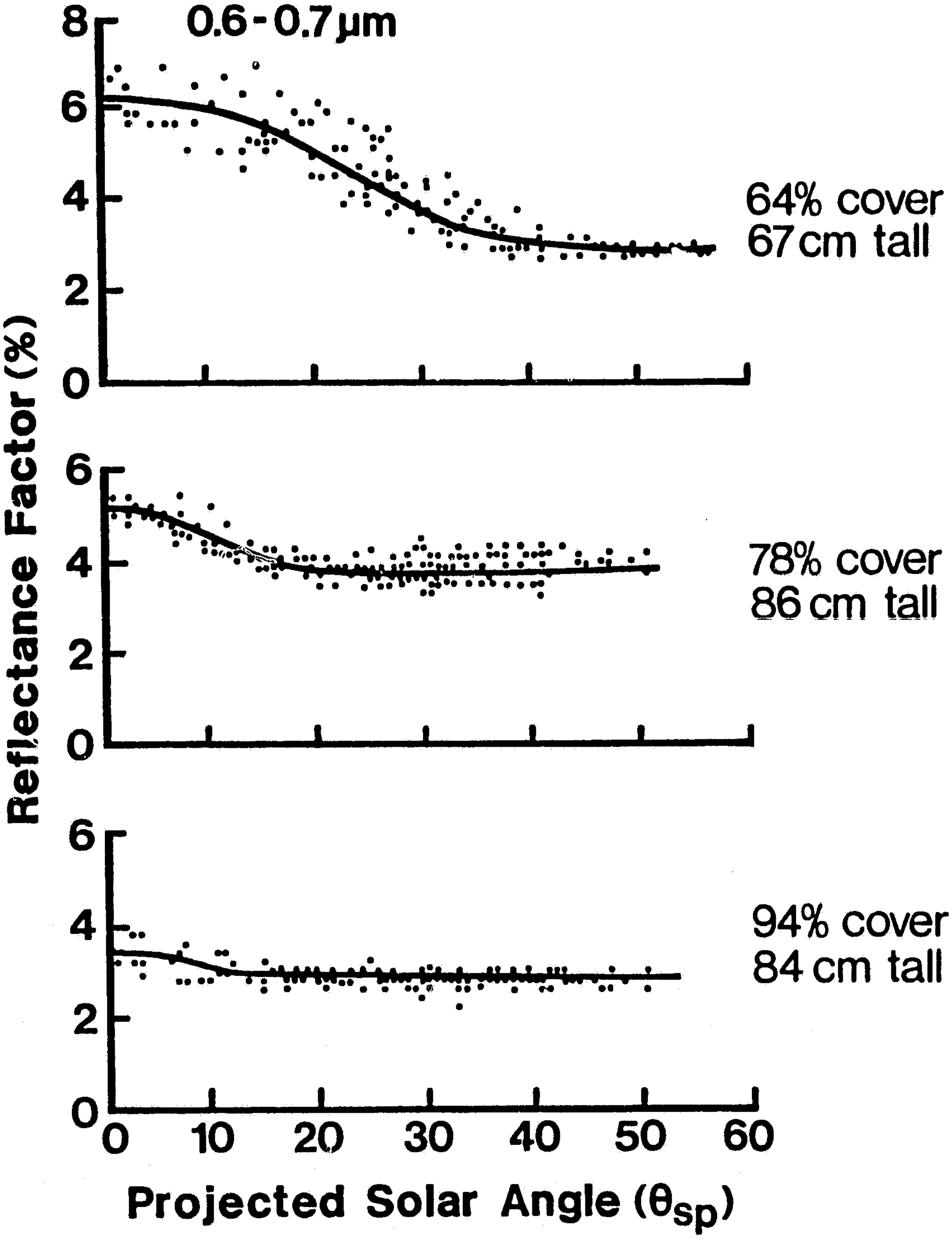



Figure 9. Relationship between RF in the red wavelength band (0.6-0.7 µm) and projected solar angle $\theta sp$ for three different canopies.

## Summary and Conclusions

The objective of this research was to identify the physical causes of diurnal changes in the reflectance factor of a row crop canopy. This is important when the measured reflectance factor in the visible region of a given plot may vary 100 percent or more during the day due to varying amounts of shadow within the canopy. A function called the projected solar angle, θsp, that includes both the solar zenith and azimuth angle plus the row azimuth angle, descibes the changes in shadow and, thus, the diurnal changes observed in reflectance factor. Canopy geometry was a key factor determining both the diurnal range of the spectral response and the critical angle where further increases in Osp did not lower the RF measured. The soil component of the scene was then completely shadowed.

The effect of solar zenith angles between 20 and 60 degrees on the measured reflectance was found to be nonsignificant when the RF was measured at nadir over all the plots, including the bare soil and full canopy plots. The near infrared RF and greenness function were not as sensitive to changes in solar illumination angle in the row crop canopy observed as the visible region and near infrared/red reflectance ratio. These variables may thus prove to be useful in relating spectral response to such agronomic variables as percent soil cover, leaf area index, and plant biomass over a wide range of illumination angles.

The results indicate that changes in canopy shadowing may be a significant factor, particularly in the visible wavelength region, influencing the spectral reflectance of crop canopies. A physical model accounting for this variation was developed. It will be used in future

investigations to simulate the variation which may be expected with varying row direction, amounts of canopy cover, date, time of day, and latitude.

Future studies should include a wider range of solar zenith and azimuth angles and more row azimuth angles. This objective, along with a decrease in plot to plot variability, could be obtained by placing the plot to be studied on a turntable. This would allow for a quick change in the row direction with a minimum of plot to plot variation. To study effects due to the solar zenith angle on soybean row crops more effectively, measurements should be taken at low latitudes, where the range in zenith angles will be the greatest.

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